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Multiple stellar population in the Sextans dwarf spheroidal galaxy?

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ABSTRACT
We present wide field ($33' \times 34'$) multiband (BVI) CCD photometry (down to $I \lesssim 20.5$) of the very low surface brightness dwarf Spheroidal (dSph) galaxy Sextans. In the derived Color Magnitude Diagrams we have found evidences suggesting the presence of multiple stellar populations in this dSph. In particular we discovered: *(i)* a Blue Horizontal Branch (HB) tail that appears to lie on a brighter sequence with respect to the prominent Red HB and the RR Lyrae stars, very similar to what found by Majewski et al. (1999) for the Sculptor dSph; *(ii)* hints of a bimodal distribution in color of the RGB stars; *(iii)* a double RGB-bump. All these features suggest that (at least) two components are present in the old stellar population of this galaxy: a main one with $[Fe/H] \sim -1.8$ and a minor component around $[Fe/H] \gtrsim -2.3$. The similarity with the Sculptor case may indicate that multiple star formation episodes are common also in the most nearby dSphs that ceased their star formation activity at very early epochs.

Key words: galaxies: stellar content – stars: horizontal branch – galaxies: individual: Sextans – Local Group.

1 INTRODUCTION

The Sextans dwarf spheroidal (dSph) galaxy is the least studied member of the family of dwarf galaxies that orbits the Milky Way. Discovered just a decade ago by Irwin et al. (1990), it is the Local Group galaxy with the *lowest* surface brightness ($\mu_0 = 26.2 \pm 0.5$ mag/arcsec^2), it is relatively distant ($D = 86 \pm 4$ Kpc; data from Mateo 1998), and it is projected onto a sky field significantly contaminated by foreground stars belonging to our Galaxy ($b = +42.27$). The body of the Sextans dSph is devoid of gas, but an HI cloud ($M \simeq 3 \times 10^4\ M_\odot$) with similar velocity has been recently discovered by Blitz & Robishaw (2000), $\sim 2°$ apart from the center of the galaxy.

Mateo et al. (1991) presented the first Color Magnitude Diagram (CMD) of Sextans based on CCD photometry. They obtained deep photometry of two overlapping $\sim 3.9' \times 3.9'$ fields ($V < 24$, barely reaching the Turn Off point), and a shallow photometry of nine similar fields. They derived a "globular cluster like" CMD, with a predominantly red Horizontal Branch (HB) and a large number of Blue Straggler Stars (BSS). From the analysis of the CMD, they concluded that the galaxy is dominated by a very old (~ 15 Gyr) population with a metallicity of $[Fe/H] \sim -1.6 \pm 0.2$. Da Costa et al. (1991) obtained spectra of 14 stars in Sextans, from which they derived the first estimate of the systemic radial velocity, identifying 6 member stars, and a mean metal abundance of $[Fe/H] = -1.7 \pm 0.25$ from the CaII triplet, in agreement with Mateo et al. (1991). Both teams noted that this metallicity was significantly higher than expected given the observed integrated magnitude ($M_V \simeq -9.5$) and the relation between [Fe/H] and M_V followed by the other dSphs (Mateo et al. 1998).

Suntzeff et al. (1993; hereafter S93) obtained spectra for 80 stars in the direction of the Sextans dSph, identifying 43 member stars for which they found $-2.44 \leqq [Fe/H] \leqq -1.57$ from the CaII triplet (see Da Costa et al. 1991). S93 concluded that *(a)* the mean metallicity of Sextans is $[Fe/H] = -2.05 \pm 0.04$, fully compatible with the M_V vs. $[Fe/H]$ relation of dSphs, and that *(b)* there is an intrinsic metallicity dispersion of 0.19 dex. Mateo, Fischer & Krzemiński (1995; hereafter MFK) performed a variable stars survey over a large area ($18' \times 18'$), identifying 36 RR Lyrae and 6 anomalous Cepheids, all probable members of the Sextans galaxy. They confirmed that the dominant stellar population in Sextans is old (> 10 Gyr) and they associated the previously detected BSS with a younger

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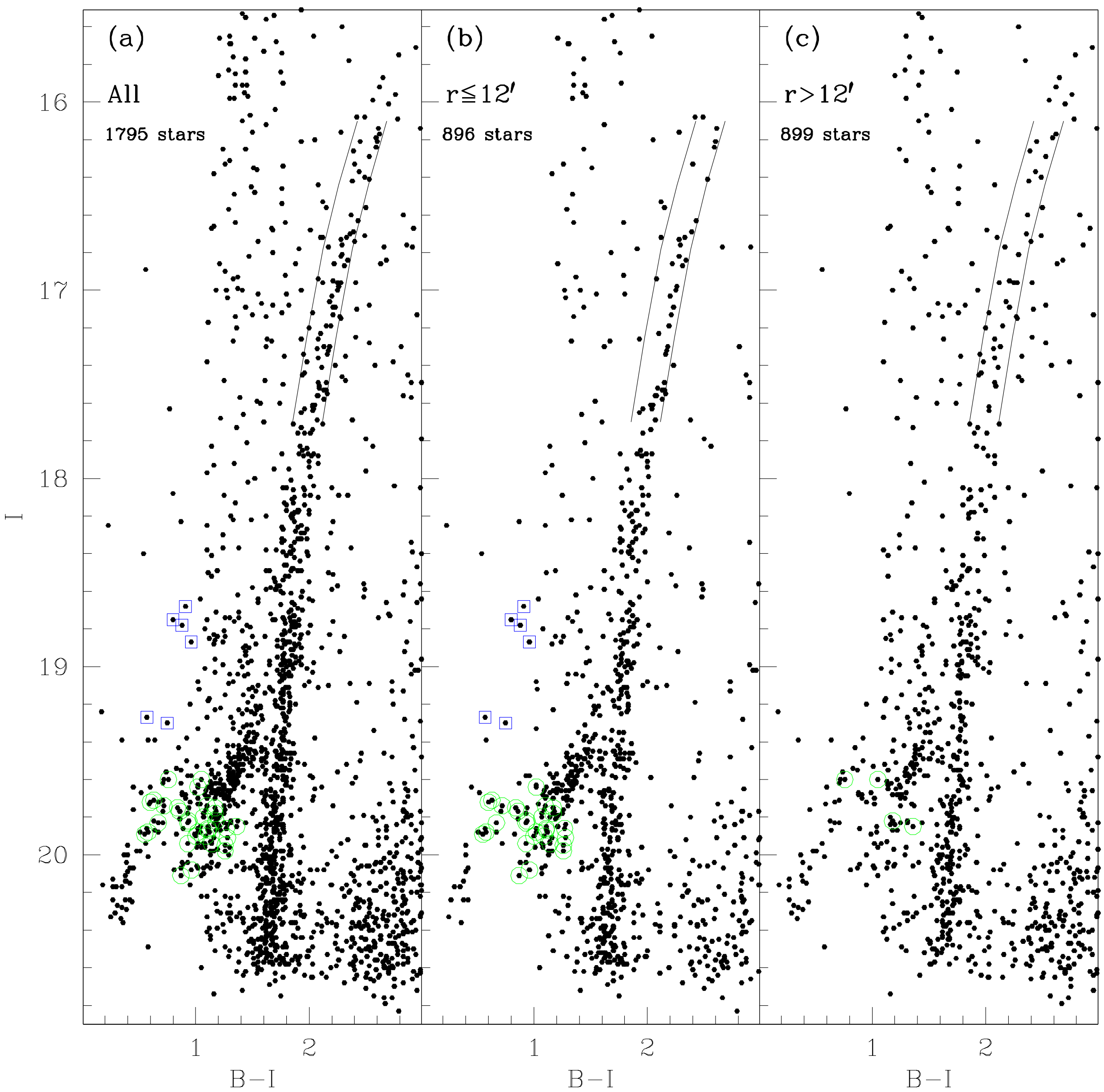

Figure 1. (I, B-I) Color Magnitude Diagrams for the Sextans dSph. Variables (from MFK) are marked with different symbols: RR Lyrae (*large open circles*) and anomalous Cepheids (*large open squares*). The typical photometric errors ($\epsilon_I, \epsilon_{B-I}$) range from (0.01,0.015) at $I = 16$ to (0.03,0.04) at $I = 20.5$. Panel *(a)*: CMD of the entire sample; panel *(b)*: stars within $12'$ from the center of the galaxy; panel *(c)*: stars with $r > 12'$. The two parallel lines approximately enclose the color range spanned by Sex RGB stars to show more clearly the different color distribution of inner and outer RGBs. The position of the center has been assumed to coincide with the star V7 by MFK, accordingly to their prescriptions.

$(2-4$ Gyr) population, comprising less than 25% of the whole stellar content. MFK estimated the overall Sextans metallicity to be $[Fe/H] \simeq -1.6$, from both the Red Giant Branch (RGB) color and the RR Lyrae stars properties. They also measured the HB morphology parameter $(P_{HB} = (B-R)/(B+R+V))$,[‡] obtaining $P_{HB} = -0.5$

‡ B, R and V are respectively: the number of stars bluer than the instability strip (B), redder than the instability strip (R) and lying inside the instability strip, i.e., the RR Lyrae variables (V).

and they noted that this value is not compatible with an old age and a metallicity as low as that found by S93. On the other hand, if $[Fe/H] \simeq -1.6$ is assumed, the HB morphology parameter turns out to be consistent with an age of ~ 12 Gyr.

Geisler & Sarajedini (1996) derived $[Fe/H] = -2.0 \pm 0.1$, with an intrinsical spread of 0.17 dex, from Washington photometry of RGB stars, in full agreement with S93. Finally, Shetrone, Côté & Sargent (2001; hereafter SCS) obtained Keck-HIRES spectra of five giants in Sextans, for which they derived $[Fe/H] = -2.85$, -2.19, -1.93, -1.93 and -1.45.

In conclusion, there is no agreement on the actual metallicity of this dSph, and indeed serious difficulties emerged in the interpretation of its HB morphology, at least if a classical "single age - single metallicity" scheme is adopted for the dominant population (see MKF).

The advent of modern wide field CCD cameras has significantly changed our view of the dSph galaxies, once believed to be prototypes of Pop II systems. Deeper photometry and larger samples have revealed that most of these systems had complex and various star formation and/or chemical enrichment histories (see Mateo 1998, van den Bergh 1999, Grebel 1999, and references therein). This can be the case also for the Sextans dSph. Given its extremely low surface brightness, it is quite possible that relevant features of the CMD have been missed, since even when observing relatively wide fields, some short-lived evolutionary sequences may not be sufficiently sampled. For example, the largest published photometric sample (MKF) for Sextans includes only 505 stars with $V \leq 21$ (i.e., ~ 0.5 mag below the HB), a significant fraction of them being foreground or background sources.

In this Letter we present wide field ($\sim 34' \times 33'$) BVI photometry (down to $V \sim 21.5$) in the Sextans galaxy and we discuss the main features of the CMD. The area covered by our study is ~ 3.5 times larger than the largest survey (MKF) published for this galaxy, so far. From the analysis of the main branches in the CMD we find several evidences suggesting the presence of two components in the main stellar population of the Sextans dSph.

2 THE COLOR MAGNITUDE DIAGRAM

One B and one I images (both 600 *s*-long) of the Sextans dSph have been obtained in January 1999 at the 2.2m ESO-MPI telescope at La Silla (Chile), using the Wide Field Imager (WFI), a mosaic camera with a total field of view of $\sim 34' \times 33'$. The observations were carried on as a back-up programme while the main targets were not visible. The seeing was $\sim 1.2''$ FWHM. The observational set-up and the photometric calibration are the same as in Pancino et al. (2000; hereafter P00).

The standard bias and flat-field correction has been applied to the data, using the NOAO *mscred* package in IRAF[§]. PSF photometry was then performed using DoPHOT (Schechter, Mateo & Saha 1993).

The observed field is remarkably contaminated by background galaxies. We retained only the sources classified as bona fide stars by DoPHOT. The automated star/galaxy classification by DoPHOT was independently (and successfully) checked using the SExtractor package (Bertin & Arnouts 1996). The test showed that our sample is not significantly contaminated by background galaxies for $I \gtrsim 19$, while no useful check was possible at fainter magnitudes.

The panel *(a)* of Fig. 1 shows the $(I, B-I)$ CMD for ~ 1800 sources detected in the WFI field of view. The steep RGB and the extended HB of the Sextans galaxy are clearly stacking over the nearly uniform background in the CMD, thus showing that the lacking of a control field is not a serious problem in the present case. We have cross-identified most of the variable stars observed by MFK (see Fig. 1). There are a number of features worth of noticing in Fig. 1a:

(i) The HB is very extended: indeed, the most notable feature in the CMD is the presence of a well populated blue tail (hereafter BHB) at $I \sim 20$ and $B-I < 0.8$. The BHB appears to lie above the mean level defined by the red HB and RR Lyrae stars. The effect is of course even more evident in the $(B, B-I)$ CMD (not shown) and strongly resembles the anomalous HB morphology noted by Majewski et al. (1999; hereafter M99) in the Sculptor dSph. This is the first time that this feature is detected in Sextans.

(ii) The RGB appears steep and well defined. However, the spread in color of the giants is much larger than the observational error, hence a sizeable intrinsic metallicity dispersion could be present. The RGB thickness is clearly visible in the region $18 < I < 19$.

(iii) The location of the bulk of the RGB stars in the $(I, B-I)$ CMD turns out to be bluer than the location of the dominant population of giants in ω Cen (see P00), suggesting that most of the stars in the Sextans dSph have $[Fe/H] \gtrsim -1.6$ (see also below). We also cross-identified all the member giants with known metallicity (from S93): there is no apparent color segregation as a function of the S93 metallicity estimates. This could be due to uncertainties in the CaII triplet measurements, and in this case high-resolution spectroscopy could help in better understanding the actual metallicity distribution.

(iv) As expected, the contamination by foreground and background sources is quite large. The sparse blob of points at $(B-I) > 2.6$ and $I > 20.5$ is probably due to the increasing number of faint and unresolved galaxies. It is interesting to note the sharp cut off in color the distribution of foreground stars occurring at $B-I \sim 1.0$ ($B-V \sim 0.4$), which corresponds to the TO color of the halo and/or thick disc of the Milky Way (Unavane, Wyse & Gilmore 1996; Morrison et al. 2000). However, on the basis of the position in the CMD, we estimate that ~ 1000 stars are likely members of the Sextans dSph: this is the largest sample of evolved stars ever published for the Sextans dSph so far.

The panels *(b)* and *(c)* of Fig. 1 shows the CMD for the stars within $12'$ from the center of Sextans and outside this circle, respectively. It is interesting to note that the relative abundance of BHB stars is larger in the outer region. The

[§] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

ratio between the number of HB stars with $B-I \leq 0.5$ (N_{BHB}) and those with $B-I > 1.1$ (N_{RHB}) is $\frac{N_{BHB}}{N_{RHB}} = \frac{13}{109} = 0.12 \pm 0.03$ for the inner sample and $\frac{N_{BHB}}{N_{RHB}} = \frac{18}{74} = 0.24 \pm 0.06$ for the outer one. Even more remarkably, the upper RGB stars with $r \leq 12'$ are tightly gathered along the red edge of the color distribution while the outer ones are evenly spreaded over the whole color range spanned by the total sample of RGB (delimited in Fig. 1 by two parallel curves enclosing the RGB, reported as an aid for the eye). This kind of population gradient has been observed in many dSph galaxies (Mateo 1998 and references therein; see also M99 and Hurley-Keller, Mateo & Grebel 1999 for the case of Scl that is particularly relevant here) and provides a first indication on the possible composite nature of the dominant population in Sextans. Unfortunately, the low total number of Sextans stars prevents further detailed study of the inner and outer RGB samples separately. Thus, in the following discussion, we will refer to the total RGB sample.

3 A COMPOSITE POPULATION?

As quoted above, the most notable *new* feature discovered in this Letter is the presence of an *anomalous* blue HB tail. We find that the BHB population, defined by considering all the non-variable stars with $(B-I) < 0.8$, comprises $\sim 17\%$ of the entire HB population. With this definition, the P_{HB} parameter turns out to be $P_{HB} \simeq -0.4$, suggesting a bluer morphology with respect to the one estimated by MKF. Note that this value should be considered as a lower limit, since the foreground contamination can significantly enhance the counts in the R bin, leaving untouched the B one.

Some of the features noted in the CMD of Sextans have been recently found in the CMD of another dSph: the Sculptor galaxy by M99. In particular, they interpreted the apparent mismatch between the HB tail and the RR Lyrae level in Sculptor as the signature of the presence of two populations, a very metal poor one (at $[Fe/H] \sim -2.2$) responsible for the brighter BHB, and a more metal rich one (at $[Fe/H] \sim -1.5$) associated with the red HB (see Hurley-Keller et al. 1999 for a different view). Their hypothesis was supported also by the Luminosity Function (LF) of the RGB, in which two distinct RGB bumps were detected. Intrigued by the similarity, we proceeded in a deeper analysis following M99. Unfortunately, the extremely low surface brightness of Sextans and the foreground contamination make our analysis more uncertain, despite the fact that we observed a significantly wider field than M99.

The CMD of Sculptor presented by M99 is in the $(V, B-V)$ plane, for this reason, in order to perform a direct comparison among the various features in the CMDs of the two dSph, we retrieved a 300 s V exposure of Sextans (obtained in January 2000) from the WFI archive. This image covers approximately the same field of our B, I dataset. The absolute calibration of the V data was obtained using ~ 350 stars in common with MKF.

In Fig. 2 we compare our $(V, B-V)$ CMD of Sextans with the one of Sculptor (from M99[¶]). The similarity of the two CMDs, and in particular of their *HB morphology* is indeed striking, suggesting that the presence of populations with different mean metallicities may be also the origin of the Sextans *anomalous* HB morphology.

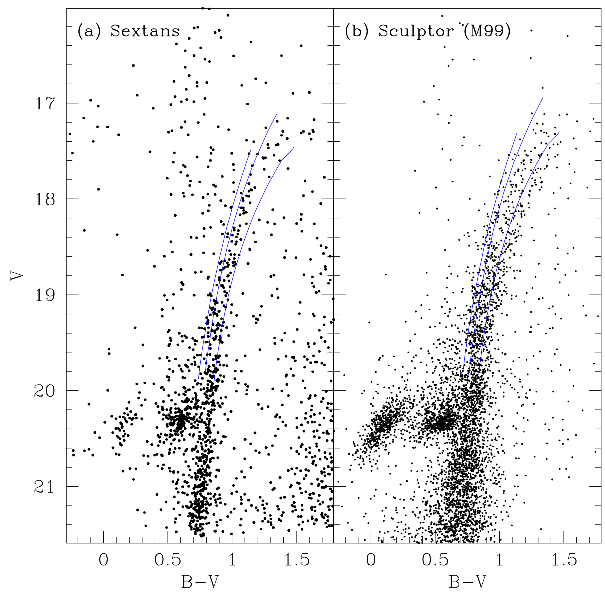

Figure 2. (V, B-V) CMDs for Sextans (*panel (a)*, this work) and Sculptor (*panel (b)*, from M99). RGB ridge lines of template globular clusters (from Ferraro et al. (1999) are over-plotted. From blue to red: NGC 5053 ($[Fe/H]_{ZW} = -2.58$), M 68 ($[Fe/H]_{ZW} = -2.09$), and M 3 ($[Fe/H]_{ZW} = -1.66$). The CMD presented in *panel (a)* has been obtained by coupling the photometry from our 600 s B exposure with the one from 300 s V exposure we retrieved from the WFI archive.

The RGB ridge lines of three template globular clusters taken from Ferraro et al. (1999; hereafter F99) have also been overplotted on the CMDs, once corrected for distance modulus and reddening according to Mateo (1998). The adopted templates are (from the bluest to the reddest ridgeline) NGC 5053, NGC 4590 (M 68) and NGC 5272 (M 3), with metallicities of $[Fe/H] = -2.58, -2.09$ and -1.66 in the Zinn & West (1984; hereafter ZW) scale, and of $[Fe/H] = -2.51, -1.99, -1.34$ in the Carretta & Gratton (1997; hereafter CG) scale, respectively. Here we quoted the CG scale just for completeness: since most previous estimates are in the ZW scale, we adopt the ZW metallicity scale throughout the rest of this Letter.

First, we note that the vast majority[‖] of the Sextans RGB stars lie to the blue side of the M 3 ridgeline. This

¶ The M99 dataset was kindly provided in electronic form by M.H. Siegel.

‖ A few stars seem to run parallel to the main RGB sequence, at the red side of the M 3 ridgeline. The membership of these stars is to be assessed spectroscopically: they are likely to be foreground stars, but they may also be part of a minor metal rich component of the galaxy.

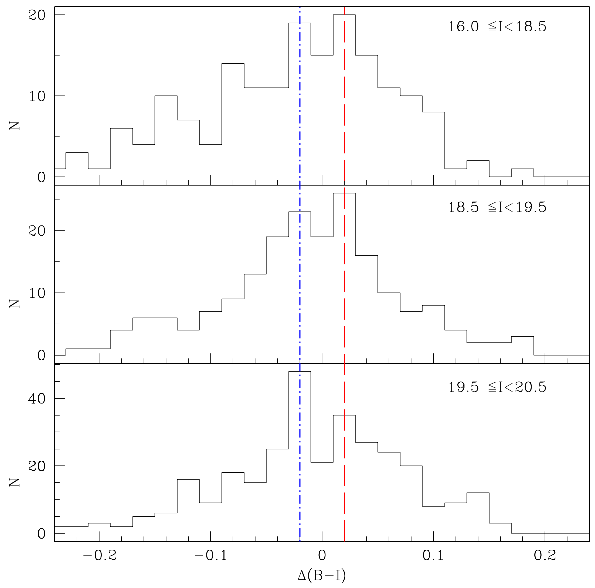

Figure 3. Distribution of the color deviation from the ridge line of the Sextans giants in three different ranges sampling more than 4 mag along the RGB. The modes of the two components are marked by vertical lines crossing the panels.

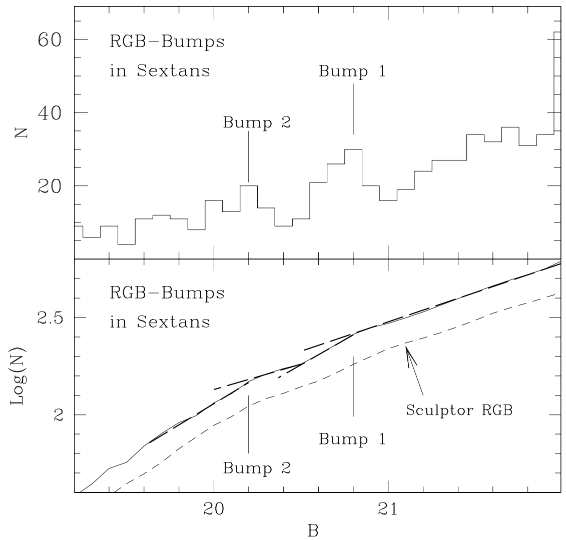

Figure 4. *Panel (a)*: differential LF of the Sextans RGB. *Panel (b)*: cumulative logarithmic LF of the same sample. The two distinct bumps are clearly indicated. In *panel (b)* the LF of Sculptor from M99 is also reported for comparison, after the application of an arbitrary shift.

means that $[Fe/H]_{ZW} \sim -1.6$ is, at most, an upper limit to the metallicity distribution of the main population of the Sextans dSph. The main fraction of the Sextans giants is enclosed between the ridgelines of M 3 and M 68 (suggesting the presence of a main population with $[Fe/H] \sim -1.8$), while a minor fraction ($\sim 25\%$) lies between the ridgelines of M 68 and NGC 5053 (suggesting the presence of a lower metallicity component with $[Fe/H] < -2.1$). These mean metallicities are in good agreement with the previous estimates by S93, SCS and Sarajedini & Geisler (1996), confirming the presence of a quite large metallicity spread in Sextans ($-2.6 \gtrsim [Fe/H]_{ZW} \gtrsim -1.6$). Moreover, it is interesting to note that the most metal-poor component fraction ($\sim 25\%$) turns out to be consistent with the BHB population fraction ($\sim 17\%$, see above). This result further supports a possible connection between the metal-poor RGB component and the BHB.

In order to obtain better constraints on the metallicity distribution in the Sextans dSph we analyzed in more detail the RGB colour distribution shown in Fig. 1. We derived a mean ridge line for the whole RGB following the method adopted by F99 and we computed the color deviations $\Delta(B-I)$ of RGB stars from the ridge line. The distribution of $\Delta(B-I)$ in three magnitude ranges sampling the entire extension of the observed RGB is shown in Fig. 3. While the distribution is quite broad (also because of the foreground contamination) the core of the distribution presents two separate peaks at the same position in all the considered ranges. The suggested bimodal color distribution of the giants in Sextans, already partially apparent in Fig. 1b,c, provides further support for the presence of (at least) two stellar populations of different metallicity.

Finally, a further remarkable similarity with the case of Scl is shown in Fig. 4, where the RGB-LFs are plotted, following the standard approach to reveal the RGB bump position (see Fusi Pecci et al. 1990, F99 and references therein). *Two distinct RGB bumps are detected along the Sextans RGB*, the fainter one (B1) is located at $B = 20.8 \pm 0.1$ (corresponding to $V \simeq 19.95$) and the brighter one at $B = 20.2 \pm 0.1$ (corresponding to $V \simeq 19.35$). The luminosity of the RGB bump depends primarily on the metal content of the associated population and only weakly on age: more metal deficient populations have brighter bumps. Hence the double RGB bump can be interpreted as the signature of the coexistence of two populations of different mean metal content, as in M99. Assuming $(m-M)_V = 19.79 \pm 0.15$ from MFK, we derive $M_V^{B1} = 0.16$ and $M_V^{B2} = -0.44$, respectively. We can use the absolute magnitude of the bump in order to get a rough estimate of the metallicity for the two populations, by using the following relation:

$$M_V^{bump} = 0.87[Fe/H]_{ZW} + 1.74$$

which has been derived from the F99 data-set. From the absolute magnitudes obtained above, we finally find $[Fe/H]_{ZW}^{B1} \sim -1.8$ and $[Fe/H]_{ZW}^{B2} \sim -2.5^{\star\star}$

** Note that this value is quite uncertain, since the relation derived above is valid only in the range $-0.2 \gtrsim [Fe/H]_{ZW} \gtrsim -2.2$ and significant deviation from linearity cannot be excluded outside this range.

4 CONCLUSION

From all the above results, a remarkably self-consistent scenario emerges, i.e., *the dominant population in Sextans consists of two distinct components, both quite metal deficient: a minor one (∼ 20% of the whole) with $[Fe/H]_{ZW} \gtrsim -2.3$, and the most conspicuous one with $[Fe/H]_{ZW} \sim -1.8$.* The most metal poor population is likely to be associated with the BHB and with the bright RGB bump B2, while the major component should be related with the RHB and the B1 bump. As in many other dSphs the component associated with the BHB stars shows a more extended radial distribution with respect to the RHB and the reddest RGB stars. This scenario is consistent with the results by S93, SCS and Sarajedini and Geisler (1996), leaving Sextans in the expected place in the M_V vs. $[Fe/H]$ relation of dSphs. Since it is reasonable to presume that the metallicity difference of the two components may be associated to an age difference (up to a few Gyr), the peculiar HB morphology can be much more easily understood in the above framework than in an usual "single-metallicity" scheme, that has been proved to be inadequate for all the other dSphs (Mateo 1998; Grebel 1999). However, it is important to remark that a confirmation of the above framework has to wait for deeper photometry, reaching the Main Sequence to well below the Turn Off point, and possibly high resolution spectroscopy of larger samples. Lacking these fundamental pieces of information, also other interpretations may be viable (see, f.i, M99 and Hurley-Keller et al. 1999).

The most nearby dSph galaxies host only modest (if any) intermediate-age populations (Mateo 1998; van den Berg 1999) and they are almost completely gas depleted in their main body[††] (Blitz & Robishaw 2000). It has been convincingly suggested that the interaction with the tidal field and/or with the hot gaseous halo and/or with the early stellar wind from the Milky Way were particularly efficient in stopping the main evolutionary path of these innermost and least massive satellites at early epochs (see van den Bergh 1994; Blitz & Robishaw 2000, and Bellazzini, Fusi Pecci & Ferraro 1996). Despite this, at least some of them (Sextans, Sculptor) seem to host multiple populations, indicating that their stellar content *was not originated in a single burst* and that a significant chemical evolution took place before their gas reservoirs were swept out (see Tamura, Hirashita & Takeuchi 2001). Hence, these galaxies may provide an unique view of a very early phase of the evolution of stellar systems, for which there is no other counterpart, except for the rare very metal poor stars that are dispersed in the vast Galactic halo (Cayrel 1996; Beers 1999; Morrison et al. 2000).

[††] Sculptor, Ursa Minor, Draco and Sextans seem indeed quite similar in stellar and gas content as well as in distance from the center of the Galaxy and other characteristics. In particular, SCS claim that the UMi, Dra and Sextans dSphs *(a)* share *very similar* abundance patterns, distinct from those typical of the Galactic halo stars, *(b)* their dominant stellar populations are quite metal deficient, with no star more metal rich than $[Fe/H]_{ZW} \sim -1.4$, and *(c)* many of their stars reach a degree of metal deficiency ($[Fe/H]_{ZW} \leq -2.5$) not spanned by existing Galactic globulars.

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